SIMULTANEOUS POSITION MEASUREMENTS OF PROTONS AND ANTI-PROTONS IN THE TEVATRON

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Abstract

Fermilab has embarked upon a program to upgrade the electronics of the Beam Position Monitor (BPM) system that measures the transverse position of the beams inside the Tevatron collider. The upgrade system improves on the current system in precision, accuracy and reliability. A new feature in the upgraded system is the ability, when both protons and anti-protons are present in the Tevatron, make simultaneous measurements of the closed orbit position of both beam species. This paper will present one of the methods for achieving the simultaneous measurement and will present results from the commissioning data that demonstrate that the system achieves its requirements.

INTRODUCTION

The stripline directional-coupler design of the Tevatron BPM pickups[1] would ideally offer perfect isolation between signals from particles traveling in opposite directions. In reality, little more than 26dB isolation is available at the 53 MHz processing frequency. With the now-typical 10:1 proton-to-antiproton bunch intensity ratio, this isolation alone is insuf£cient to support millimeter-accuracy antiproton ($\bar{p}$) position measurements in the presence of protons (p). An accurate and manageable solution to this interfering signal problem is required for $\bar{p}$ measurements now and, as $\bar{p}$ intensity increases, to facilitate elimination of $\bar{p}$ bias on p measurements in the future. Two avenues of approach are suggested: 1) separate the signals in the time domain, and 2) calibrate the cross-talk in the frequency domain and make compensation before computing beam position. This paper discusses the second approach; the £rst is discussed elsewhere [2]. An overview of the BPM upgrade project has has also been contributed to this conference [3].

METHODOLOGY

Each BPM station consists of two stripline pickups, referred to as the A and B pickups, each of which is read out at both ends, referred to as the p and $\bar{p}$ ends. If the pickups were perfectly direction-coupled, the signals from each beam species would pass 100% into the end named after it. The four signals from each BPM station are are passed through a band-pass £lter, centered at 53 MHz, and into an Echotek digital receiver board, which is programmed to measure the Fourier amplitude of each signal in a narrow frequency band around 53 MHz. A single raw measurement produced by this system consists of 4 complex numbers, A_p, B_p, $A_{\bar{p}}$ and $B_{\bar{p}}$. Further details of the signal processing may be found elsewhere [3].

Insert para stating requirements.

In Collider operation, the Tevatron beam consists of 36 bunches each of counter-circulating p's and $\bar{p}$'s within the common beam tube. For the measurements discussed here, the the digital receiver board is programmed in closed orbit mode; that is, it integrates over approximately 50 turns of the Tevatron, which corresponds to a resolution bandwidth of about 1 kHz. This measurement is averaged over all of the bunches in the machine and over many turns of each bunch. The integration time is suf£ciently long to average out the betatron oscillations but not the synchrotron oscillations. Moreover, the long integration time ensures that the method requires only coarse timing, $O(100\,\mathrm{ns})$, and the narrow resolution bandwidth reduces the dependence of the position measurement on bunch shape.

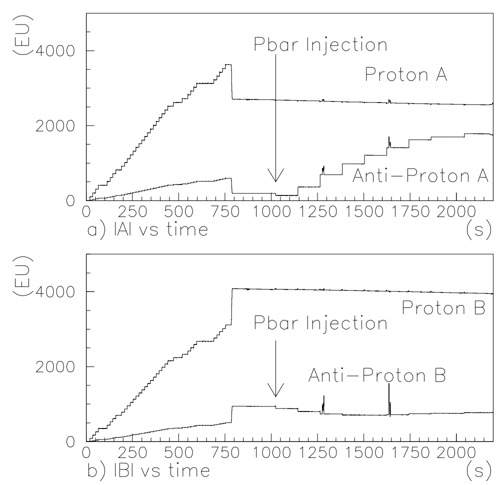

Figure 1: Magnitudes of the raw signals on the four channels from the BPM HB34. The time axis is in seconds from the start of the data set.

Figure 1 shows the magnitudes of the signals from each of the four channels on one BPM for the £rst 36 minutes of a Tevatron shot. On the $|A_p|$ and $|B_p|$ traces, one can see the 36 steps corresponding to the injection of 36 p bunches. These bunches are injected onto the central orbit. At about 800 s the separators are energized, moving the beam onto the p helix and giving rise to steps in $|A_p|$ and $|B_p|$. The vertical arrows mark the beginning of the $\bar{p}$ injection. The $|A_{\bar{p}}|$ and $|B_{\bar{p}}|$ traces to the left of the arrow show that the p contamination on the $\bar{p}$ channels is signi£cant. The two glitches in the traces, near 1300 and 1600 s, occur when the $\bar{p}$ bunches are cogged relative to the p bunches.

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In £gure 1 there is, as expected, no evidence for signi£cant $\bar{p}$ contamination on the p cables. Until the Tevatron $\bar{p}$ currents are increased signi£cantly the p raw measurements will be used without correction. The $\bar{p}$ raw measurements, on the other hand, need to be corrected and studies have shown that a linear model meets the speci£cations:

$$\begin{aligned} A'_{\bar{p}} &= A_{\bar{p}} - aA_p - bB_p \\ B'_{\bar{p}} &= B_{\bar{p}} - cB_p - dA_p, \end{aligned} \tag{1}$$

where the primed quantities are the corrected ones and where a, b, c, d are complex parameters, referred to as cancellation coef£cients. To determine these coef£cients two sets of raw measurements are taken, one at a time, t_1, just before the helix opens and another at a time t_2, a few seconds later, just after the helix opens. Under normal operations there is insigni£cant loss of beam during the opening of the helix and one may make the approximations that, $A'_{\bar{p}}(t_1) = A'_{\bar{p}}(t_2)$ and $B'_{\bar{p}}(t_1) = B'_{\bar{p}}(t_2)$. Using the two raw measurements and this approximation, one can invert Equation 1 and solve for the cancellation coef£cients.

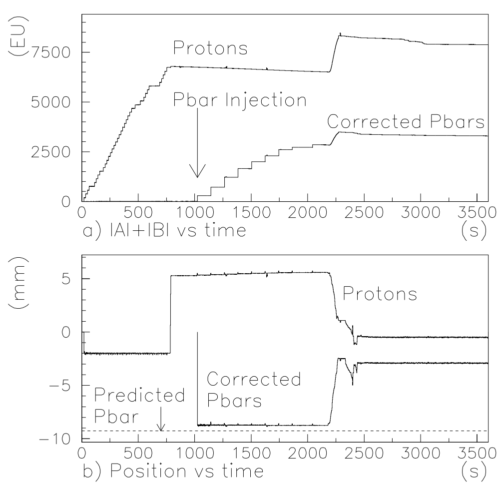

Figure 2: Sum signals and positions, after corrections, computed from the same data as used in Figure!1.

Figure 2a) shows $|A| + |B|$ for both beam species for the £rst hour of a shot.[1] For a constant beam energy, $|A| + |B|$ is proportional to the beam intensity. It is refered to here as the sum signal because the energy is not constant throughout the data set. [2] The vertical arrow marks the ime of the £rst $\bar{p}$ injection. The $\bar{p}$ sum signal before this arrow provides a £rst check on the quality of the cancellation: it is typically 5 to 10 counts, well below the level from the true $\bar{p}$ signal, but above the noise of the system when no beam is in the machine, 1 to 3 counts.

The beam position for either species, in mm, is computed as,

$$P = 26 \frac{|A| - |B|}{|A| + |B|} \tag{2}$$

where the constant 26 mm is determined by the geometry of the stripline pickups. While additional corrections are important for operation of the Tevatron, they would only complicate this paper and have been ignored. Figure 2b) shows the p and $\bar{p}$ positions for the same time period as Figure 2a). One feature of the this £gure is the opening of the helix, seen in the p trace.

There are no intentional changes to the central orbit during the opening of the helix and the $\bar{p}$ injection. Therefore one can predict the expected position of the $\bar{p}$ orbit at that time: it is the mirror image, about the central orbit, of the p orbit. In Figure 2b) a dashed horizontal line is drawn at the predicted $\bar{p}$ position, obtained using the p position immediately before and after the opening of the helix. The measured position agrees with the prediction to within 400 μm, which is within the accuracy speci£cation of 1 mm.

As the beam energy ramps up, near at time of 2200 s, the separator voltages are held constant. Therefore both beam species move at the same rate towards the central orbit. This is qualitatively observed in the data but the comparison is not exact because the central orbit does change during the ramp. After the energy ramp the beams are squeezed and brought into collision, during which time there are large changes to the central orbit.

Insert para stating resolutions.

It was previously stated that the residual from the cancellation procedure is about 10 counts in the sum signal. Consider a worst case senario in which all of the the excess is on one of the channels. Inspection of Figure 2a) and Equation 2 shows that this will result in a position bias of order 100 μm, well within the accuracy requrirement.

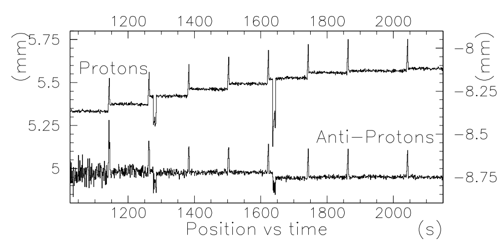

Figure 3: Detail of Figure 2b) during $\bar{p}$ injection. The left(right) scale is for the p($\bar{p}$) position.

Figure 3 shows a detail of Figure 2b) during $\bar{p}$ injection. This provides a another check on the quality of the cancellation of the p contamination. When that cancellation is poor, the $\bar{p}$ position trace will show large steps at each $\bar{p}$ injection, as will be shown in Figure 5. In Figure 3, on the other hand, the $\bar{p}$ position is stable to better than 100 μm throughout the $\bar{p}$ injection. The conclusion is that the cancellation is excellent.

Figure 3 £gure also provides evidence for $\bar{p}$ contamination on the p position. The effect is about 300 μm, well below the accuracy speci£cation of 1 mm. It is understood in

[1]The unadorned symbols A and B always refer to the raw p measurements and the corrected $\bar{p}$ measurements.

[2]Both traces show a rise in the sum signal at a time of about 2200 s. This is an artifact due to the ramping of the Tevatron energy from 150 GeV to 980 GeV.

principle how to correct for this contamination but doing so would not result in signi£cant operational improvements at the current $\bar{p}$ intensities. Moreover, calibrating this correction would probably require $\bar{p}$ only stores, a pro¤igate use of $\bar{p}$'s unless a large operational improvement is promised. The injection bumps and the cogging operations are also clearly seen in Figure 3.

One of the Tevatron tune up steps is to inject a p bunch and then energize the separators with the opposite polarity, which places the p bunch on the $\bar{p}$ helix. Figure 4a) shows

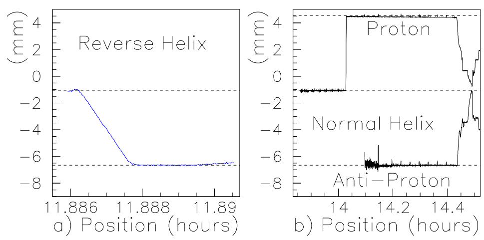

Figure 4: Reverse helix tests. The time axis is time of day, in hours.

the measured p position during one of these reverse helix stores. Horizontal dashed lines are drawn at the positions of the central orbit and the $\bar{p}$ orbit determined from this data. Figure 4b) shows the measured beam positions for a shot which followed soon after. The two horizontal lines drawn on a) have been repeated in b). A third horizontal line has been drawn on b) at the position of the p helix, mirror image of the $\bar{p}$ helix in the central orbit. Inspection of the £gure shows that the central orbit has moved by about 50 μm between shots. It also shows that the $\bar{p}$'s are measured to be at the predicted position to better than 100 μm and that the p's are at the mirror image position with an accuracy of about 150 μm. These deviations are within the speci£ed tolerances.

In order to further test the self consistency of the upgraded BPM electronics, there is a plan for a p only store with the separators off. During this store the measured p position will trace out the central orbit from initial p injection to the initiation of collisions. Immediately following this study, a normal physics shot will be done and the measured p and $\bar{p}$ positions will be compared to the central orbit determined in the p only store. If there are signi£cant deviations from the expected mirror image model, a correction scheme will be developed.

The cancellation coef£cients vary from one BPM to the next, presumably due to material and construction tolerances. The coef£cients for a given BPM also change signi£cantly from store to store. The source of this effect is believed to be store to store changes in the unmeasured transverse coordinate.[3] The scale of the store to store variation is illustrated in Figure 5. The upper points in show the $\bar{p}$ position for a particular shot using the cancellation coef£cients computed at the helix open of the same shot. The lower points show the positions for the same shot but computed using the cancellation coef£cients from a shot 7 days earlier. The older cancellation coef£cients do a much

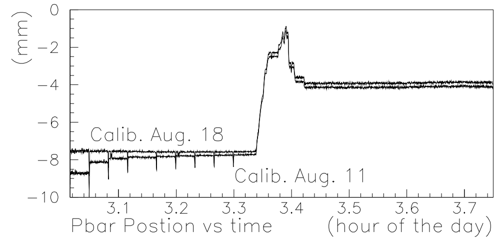

Figure 5: Variation store to store.

poorer job, particularly at low $\bar{p}$ currents when the residual contamination is a much larger fraction of the total signal. When all $\bar{p}$ bunches have been injected, the bias from the state calibration is about 500 μm, which is within requirements. When only a few bunches have been injected, however, the bias is outside of the requirements. To address this an automated procedure to recompute the cancellation coef£cients every shot is being developed.

CONCLUSIONS

This note has described the so called "frequency domain" method for measuring the $\bar{p}$ postion using the upgraded Tevatron BPM system. Using data taken during the commissioning period, the method has been shown to meet the stability requirements. The method also passes self consistency tests for its accuracy but no absolute accuracy test have been performed.

REFERENCES

[1] A reference to describe the stripline pickups.

[2] R. Webber *et al.*, "Using Time Separation of Signals to Obtain Independent Proton and Antiproton Beam Position Measurements Around the Tevatron", submitted to PAC05, May, 2005.

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[4] M. Martens *et al.*. "Tevatron Beam Position Monitor Upgrade Requirements", Fermilab Beams-doc-554, http://beamdocs.fnal.gov/cgi-bin/public/DocDB/ShowDocument?docid=554.

[5] S. Pordes *et al.*, "Measurement of Proton and Anti-proton Intensities in the Tevatron Collider", PAC2003 Proceedings,p.2491. http://library.fnal.gov/archive/2003/conf/Conf-03-146-E.pdf

[3] The response of a horizontal measuring BPM, for example, depends on the vertical position of the beam as it passes through that BPM.